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Investigation of Integrated Rectangular SIW Filter and Rectangular Microstrip Patch Antenna Based on Circuit Theory Approach

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Abstract—**This paper presents an investigation based on the resonant circuit approach to characterize an integrated microwave filter and antenna from a lumped element prototype. This approach is used to design an integrated filter and antenna to reduce the overall size of the physical dimensions of the RF/microwave front-end subsystem. This study focuses on the integration of a rectangular Substrate Integrated Waveguide (SIW) filter with a rectangular microstrip patch antenna to produce a filtering and radiating element in a single device. The physical layouts of the SIW filter and rectangular microstrip patch antenna based on single- and dual-mode will be developed. To prove the concept, the integrated microwave filter and antenna at a center frequency of 2 GHz is demonstrated and validated through simulation and laboratory experiments. The experimental performance yielded promising results that were in good agreement with the simulated results. This study is beneficial for microwave systems, given that the reduction of the complexity of design and physical dimension as well as cost are important for applications such as base stations and multiplexers in wireless communication systems.**

Keywords-Resonant Circuit; microwave filters; antenna; bandpass filters; substrate integrated waveguide

I. INTRODUCTION

The recent growth of wireless communication systems has been improving at an unprecedented pace. This evolution gives rise to opportunities for researchers to invent wireless products and services such as Global System for Mobile Communications, Long Term Evolution, Wireless Local Area Networks, and satellites, including the design of microwave devices, such as filters and antennas [1]–[3]. Most of these applications require better performance in terms of transmission as well as the low profile and small size of the filter and antenna for implementation in wireless devices. Both filters and antennas are designed separately and connected using 50 Ω common reference impedance. Such integration has to be perfectly matched using suitable impedance matching to achieve the desired return loss for both elements.

The integration of filters and antennas into one module has advantages in terms of overall physical size reduction in the RF front-end subsystem. Several techniques have been proposed in [4]–[7] to realize this integration. However, the technique applied for integration in [4] and [5] using a meandered slot is difficult to design because the meandered slot structure lends complexity to the design. In [6] and [7], the filter and antenna integration is designed with an additional impedance structure. However, the structure increases the overall size of the physical layout as well as the weight and losses.

In this paper, the development of a rectangular Substrate Integrated Waveguide (SIW) filter and microstrip patch antenna based on microwave filter circuit theory is presented. The rectangular SIW filter and rectangular microstrip patch antenna are designed at a resonant frequency of 2 GHz for single- and dual-mode. This technique realizes an SIW filter and microstrip patch antenna that can be transformed for broadband applications and can also be applied as an integration technique between the microwave filter and the antenna.

The integrated microwave filter and antenna based on the cascade and multilayer approach is presented at a center frequency of 2 GHz as a proof of concept. The concept can then be customized and applied by designers at any desired and appropriate frequency. The TE_{10} mode of propagation is used as a dominant mode to realize a single-mode of the microwave filter and antenna. The TE_{10} mode is a dominant mode existing inside the rectangular waveguide that can operate over a broad spurious free bandwidth with the lowest cut-off frequency [8]–[10].

II. EQUIVALENT CIRCUIT DESIGN

In this section, a low-pass filter prototype equivalent circuit is used to produce a single-mode filter and antenna equivalent circuit is shown in Fig. 1. The inverter K_{01} represents the coupling mechanism between the input port and the resonant circuit. Fig. 2 shows the equivalent circuit of the single-mode antenna based on the low-pass prototype circuit shown in Fig. 1. Similarly, the dual-mode filter and antenna equivalent circuit (as shown in Fig. 3) can be developed based on the second order of the low-pass prototype circuit. The dual-mode filter and antenna

equivalent circuit can also be developed based on a combination of two single-mode equivalent circuits.

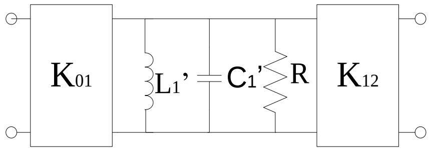


Figure 1. Low-pass filter prototype

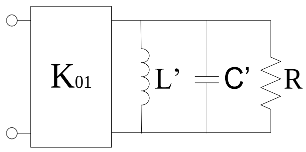


Figure 2. Single-mode circuit of patch antenna

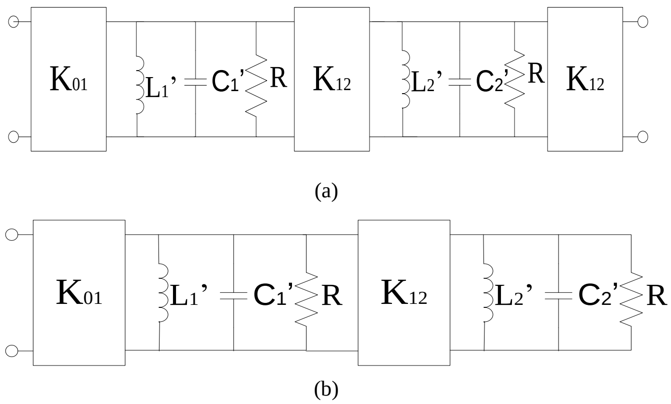


Figure 3. Dual-mode circuit of (a) filter and (b) antenna

The impedance inverter $K_{r,\ r+1}$ and the capacitance C_r value of the low-pass prototype can be determined using [11]:

$$C_r = \frac{2}{\eta}\sin\left[\frac{(2r-1)\pi}{2N}\right] \tag{1}$$

$$K_{r,r+1} = \frac{\left[\eta^2+sin^2(r\pi/N)\right]^{1/2}}{\eta} \tag{2}$$

where N denotes the number of orders of the network, and η is defined as [11]:

$$\eta = sinh\left[\frac{1}{N}sinh^{-1}\left(\frac{1}{\epsilon}\right)\right] \tag{3}$$

where ϵ is the ripple of insertion loss. The antenna equivalent circuit can be transformed from the low-pass prototype equivalent circuit using [11]:

$$L'_r = \frac{1}{\alpha C_r \omega_o} \tag{4}$$

$$C'_r = \frac{\alpha C_r}{\omega_0} \tag{5}$$

where ω_o is the geometric midband frequency, α is the bandwidth scaling factor, and r is the number of orders. The resistance R acts as lossy element of the prototype circuit.

III. THEORY AND DESIGN ANALYSIS

A. *Single-mode SIW Cavity*

The rectangular waveguide is widely used in wireless communication systems for its advantage of high power handling capabilities and low loss [12]. However, the waveguide has the disadvantages in of size and cost [12][13]. Therefore, an SIW filter is applied on the rectangular waveguide to facilitate integration with a planar structure [14]. SIW is an artificial waveguide constructed on a planar substrate with periodic arrays of metalized via holes [15].

The rule of design for the rectangular SIW filter based on TE_{10} is determined by the resonant frequency from [14][15][16]:

$$f_{r(10)} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}}\sqrt{\left(\frac{\pi}{a_{eff}}\right)^2+\left(\frac{\pi}{l_{eff}}\right)^2} \tag{6}$$

For the TE_{10} mode, the efficient width, a_{eff}, and length, l_{eff}, of the resonant SIW cavity are given by [15][16][17]:

$$a_{eff} = a_{SIW} - \frac{d^2}{0.95p}\,,\ l_{eff} = l_{SIW} - \frac{d^2}{0.95p} \tag{7}$$

where a_{SIW} and l_{SIW} are the width and length of the resonant SIW cavity, respectively; and d and p are the diameter and the distance between adjacent vias, respectively. c is the speed of light in free space, μ_r is the relative permeability, and ε_r is the dielectric permeability of the substrate. The metalized via hole diameter, d, and pitch, p, can be calculated using the design rules from the following equations [17][19]:

$$d > 0.2\lambda_o \quad , \quad \frac{d}{p} \leq 0.5 \tag{8}$$

B. *Microstrip patch antenna*

The rectangular microstrip patch antenna will be used in the integration with the rectangular SIW filter for its desirable features such as light weight and low profile of the mounting structure [20]. The structure of the rectangular microstrip patch antenna is shown in Fig. 4 [21].

The physical dimension of the rectangular microstrip patch antenna can be determined by the width w_a and the length, L_a[22][23]:

$$w_a = \frac{c}{2f_c}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{9}$$

$$L_a = \frac{1}{2f_c\sqrt{\varepsilon_{eff}}\sqrt{\mu_r\varepsilon_r}} \tag{10}$$

where f_c is the center frequency, and ε_{eff} is the efficient permeability. ΔL is the extended incremental length of the patch that can be calculated using the equation below [22][23]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{11}$$

where h is the thickness of the dielectric substrate, and y_o can be calculated using [22][23]:

$$y_o = \frac{L_a}{\pi} cos^{-1} \left[\frac{150}{R}\right]^{1/2} \quad (12)$$

where R is the impedance of the feed line, and y_o is the inset feed line for microstrip patch antenna.

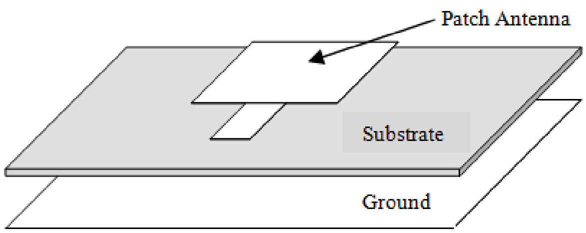


Figure 4. Microstrip patch antenna structure

C. *Integration of SIW Filter and Microstrip Patch Antenna*

The proposed integrated equivalent circuit of the rectangular SIW filter and the rectangular microstrip patch antenna can be designed in a cascaded or multilayered structure, as shown Fig. 5. The proposed physical layout for the cascaded and multilayered structure is shown in Fig. 6.

The structure provides a maximum cut-off frequency and yields better return loss of the filter aside from reducing the overall physical size. A 50 Ω transmission line is used to integrate the filter and antenna. The multilayered structure has the benefit of direct coupling without additional matching impedance between the filter and antenna as well as size reduction compared with the cascaded structure.

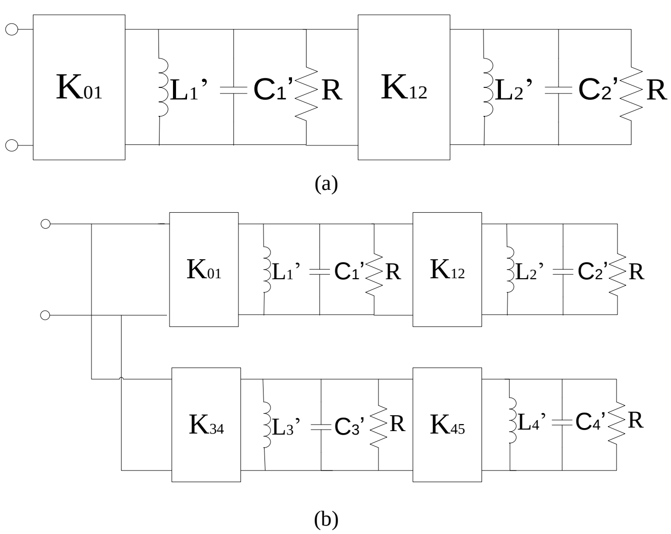


Figure 5. Integrated equivalent circuit (a) cascaded and (b) multilayer structure between the rectangular SIW filter and rectangular microstrip patch antenna

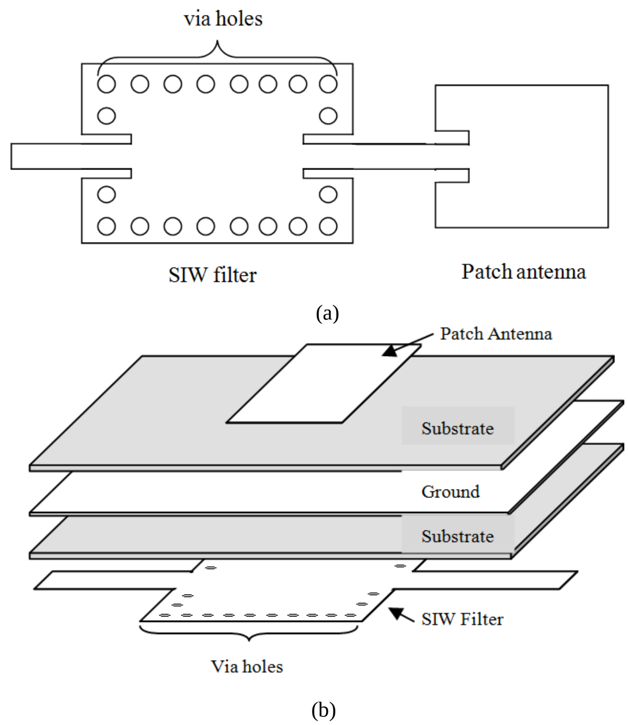


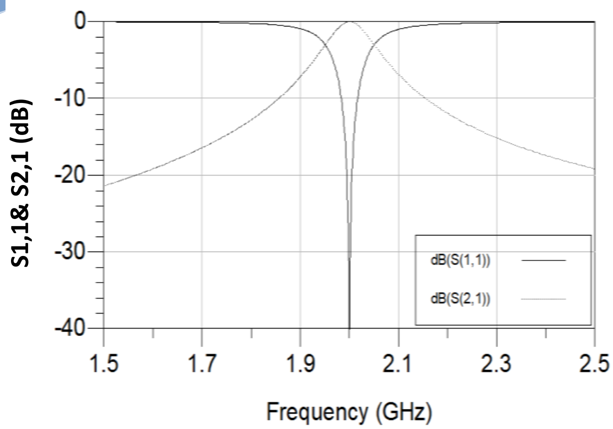
Figure 6. (a) Cascaded and (b) multilayer structure between rectangular SIW filter and rectangular microstrip patch antenna

IV. SIMULATION AND EXPERIMENTAL RESULTS

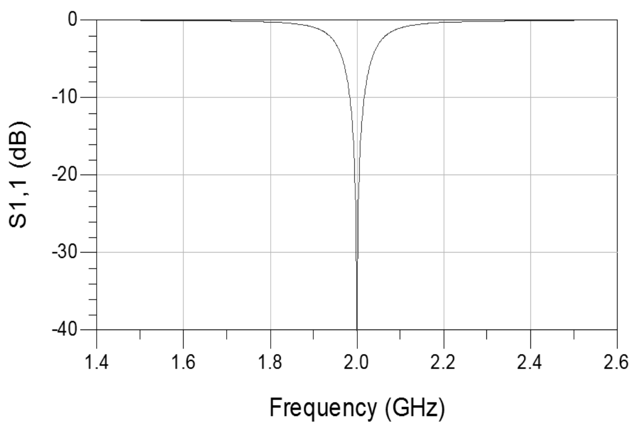
A. *Single-mode*

In this section, the design of a single-mode SIW filter and antenna equivalent circuit at a center frequency of 2 GHz will be developed using Equations (1) to (5). The coupling values $K_{01} = K_{12} = 50$, capacitance $C^{'} = 98.98$ pF, and inductance $L^{'} = 63.98$ pH for the SIW filter as well as the coupling value $K_{01} = 50$, capacitance $C^{'} = 98.98$ pF, and inductance $L^{'} = 63.98$ pH for the antenna are obtained.

Fig. 7 shows the simulated results of the SIW filter and antenna based on an equivalent circuit. A return loss (S_{11}) better than -30 dB, and insertion loss (S_{21}) at 0 dB with a bandwidth of approximately 100 MHz were achieved for the SIW filter. As for the antenna, a return loss, S_{11}, better than -30 dB with a bandwidth of approximately 31 MHz was subsequently achieved.



(a)

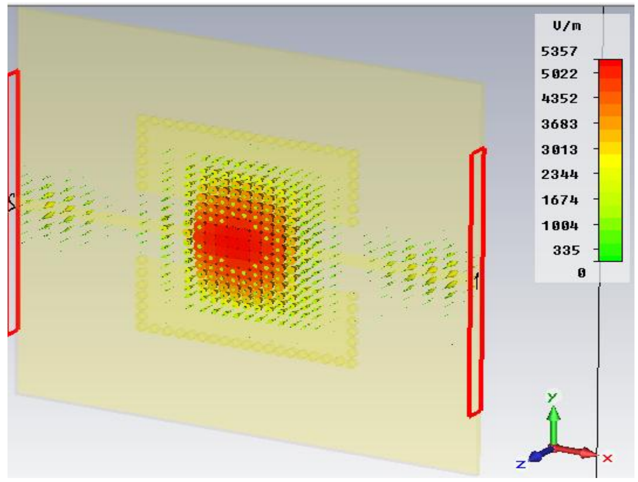


(b)

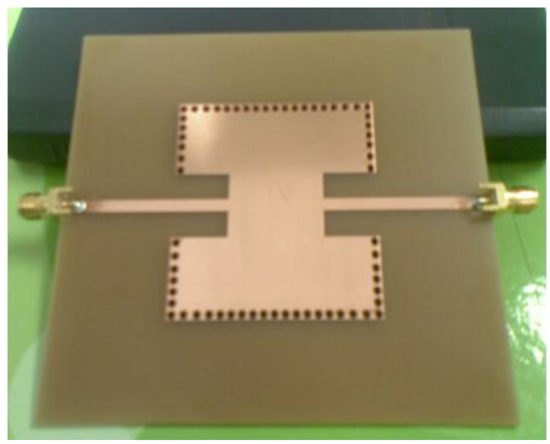
Figure 7. Simulation results of equivalent circuit (a) SIW filter (b) antenna for single-mode

The design of the filter and antenna is then simulated using CST Microwave Studio software. The devices are constructed using FR-4 on a 1.6 mm dielectric substrate thick with dielectric constant ε_r = 4.6. The thickness of copper is 0.035 mm, and the loss tangent is 0.019. The dimensions of the rectangular SIW can be calculated using Equations (6) to (8). Similarly, for the rectangular microstrip patch antenna, the dimensions can be determined using Equations (9) to (12).

The electric field (E-field) for the TE_{10} mode of the SIW filter at a center frequency of 2 GHz is shown in Fig. 8(a). The simulations show that the magnitude of E-field is concentrated at the center of the SIW cavity. The array of via-holes is used as a boundary to prevent electromagnetic leak from the SIW cavity. Fig. 8(b) shows a photograph of the physical SIW resonator filter.



(a)



(b)

Figure 8. (a) E-field distribution of rectangular SIW filter in single-mode (TE_{10}) at 2 GHz (b) Photograph ofphysical rectangular SIW filter

Fig. 9 shows the simulated and measured results on the rectangular SIW filter. The physical length l_{SIW} and width a_{SIW} of the SIW filter are 48.75 and 51.62 mm, respectively. The via-hole diameter d = 1 mm, and pitch p = 3 mm. The return loss (S_{11}) and insertion loss (S_{21}) of -6.41 dB and -0.5 dB with a bandwidth of approximately 380 MHz were obtained. In the measuring results, a center frequency of 2.045 GHz with a return loss (S_{11}) and insertion loss (S_{21}) of -21.03 and -1.57 dB, as well as a bandwidth of approximately 348 MHz were obtained. However, a frequency shift of 45 MHz from the center frequency was observed, which is attributed to the variations in dielectric permeability and manufacturing tolerance.

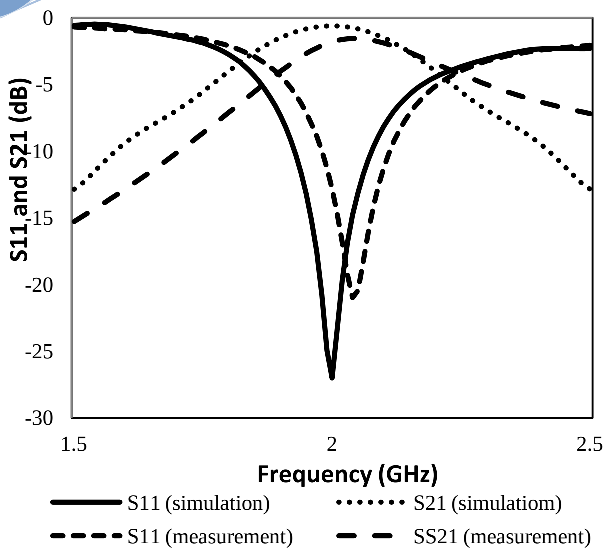
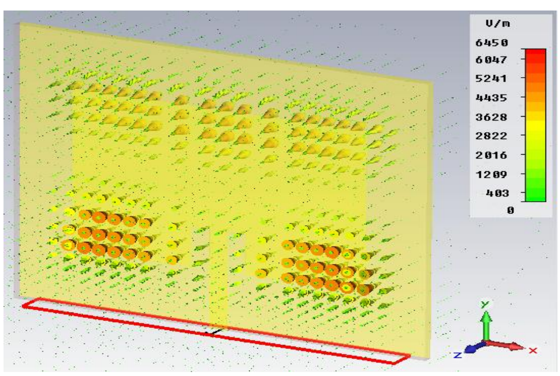
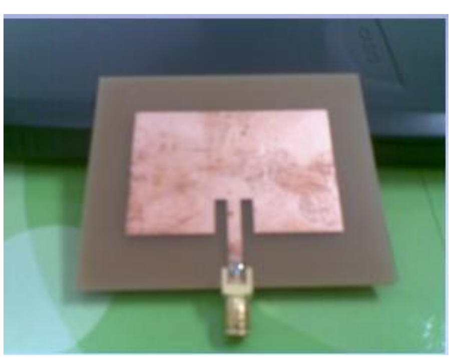


Figure 9. Simulated and measured results of rectangular SIW filter designed at 2 GHz

The electric field for TE_{10} mode in the rectangular microstrip patch antenna at 2 GHz are shown in Fig. 10(a). A significantly less concentration of E-field is observed in the patch antenna cavity because the microstrip patch antenna is a radiating device. Fig. 10(b) shows a photograph of the physical patch antenna.



(a)



(b)

Figure 10. (a) E-field distribution for rectangular microstrip patch antenna in single-mode (TE_{10}) at 2 GHz (b) Photograph of physical rectangular microstrip patch antenna

Fig. 11 shows the simulated and measured results for the rectangular microstrip patch antenna. The simulated return loss (S_{11}) is -26.81 dB with a bandwidth of approximately 41.99 MHz were obtained. As for the measuring results, the center frequency of 2.05 GHz with a return loss (S_{11}) of -26.94 dB and bandwidth of approximately 48.56 MHz were achieved. An evident frequency shift of approximately 50 MHz from the center frequency was observed, which is attributed to the variations in dielectric permeability and manufacturing tolerance.

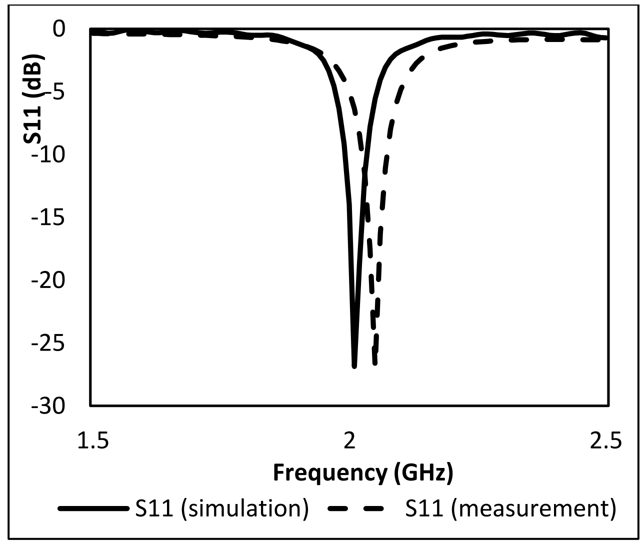


Figure 11. Simulated and measured results of rectangular microstrip patch antenna designed at 2 GHz

An investigation is then conducted on the cascaded and multilayer integration between the microwave filter and antenna. The design values for couplings, $K_{01} = K_{12} = 50$, capacitance, $C_1' = C_2' = 52.92$ pF, and inductance, $L_1' = L_2' = 119.69$ pH, are based on Fig. 5(a). Fig. 12 shows the simulated results of equivalent circuit for the cascaded and multilayer integration. A return loss (S_{11}) better than -12 dB with a bandwidth of approximately 65 MHz was achieved. Fig. 13 shows the radiation pattern for the single-mode antenna at 2 GHz. The radiation pattern represents the main lobe magnitude of 4.9 dB at a 2.0 degree direction from the origin point. The E-field distribution of the integrated rectangular SIW filter and microstrip patch antenna at approximately 2 GHz are shown in Fig. 14.

The simulated results of the integrated filter and antenna are shown in Fig. 15. A return loss (S_{11}) of -12 dB and bandwidth of 78.01 MHz was achieved, particularly in the passband. In the experimental results, a center frequency of 2.13 GHz with a return loss (S_{11}) of -4.55 dB was achieved. However, an evident frequency shift of 130 MHz from the desired center frequency was observed, which is attributed to the variations in the permittivity of the substrate, i.e., 4.6 ± 0.15, and as well as to the inconsistencies in dielectric thickness, i.e., $1.6\,mm \pm 0.025$, and manufacturing tolerance. Smaller amounts of losses in the passband are

attributed to the losses of transition from the microstrip to the SIW, copper loss through conductivity, radiation loss through the surface of the SIW filter, and losses through SMA connectors on the structure. The manufactured integrated microwave filter and antenna, with an overall length and width of 165.56 mm × 72.62 mm, is shown in Fig. 16.

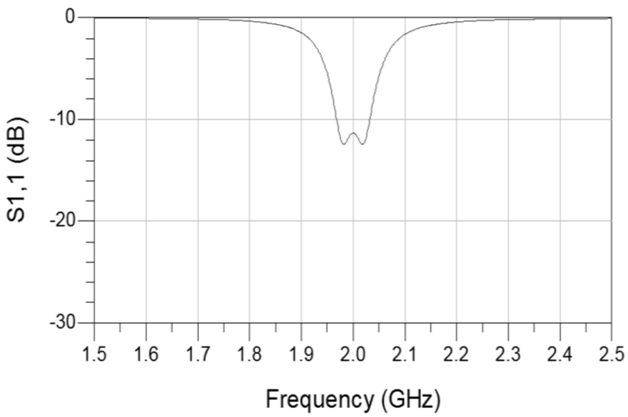


Figure 12. Simulated results of equivalent circuit for cascaded and multilayer integration design

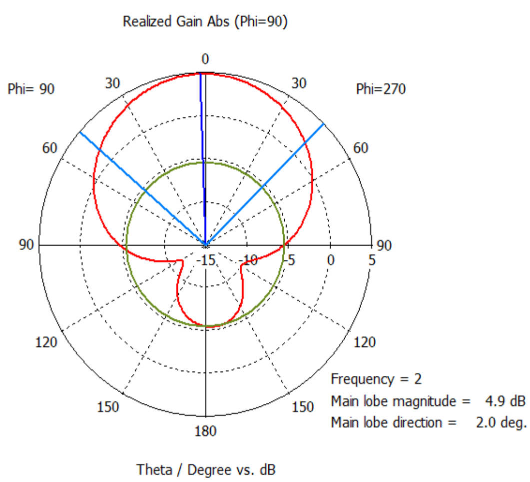


Figure 13. Simulated radiation pattern for microstrip patch antenna single-mode at frequency 2 GHz

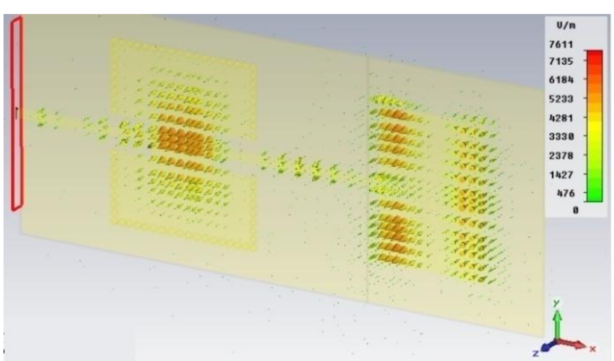


Figure 14. E-field distribution of integrated rectangular SIW filter and rectangular microstrip patch antenna in single-mode (TE_{10}) at 2 GHz

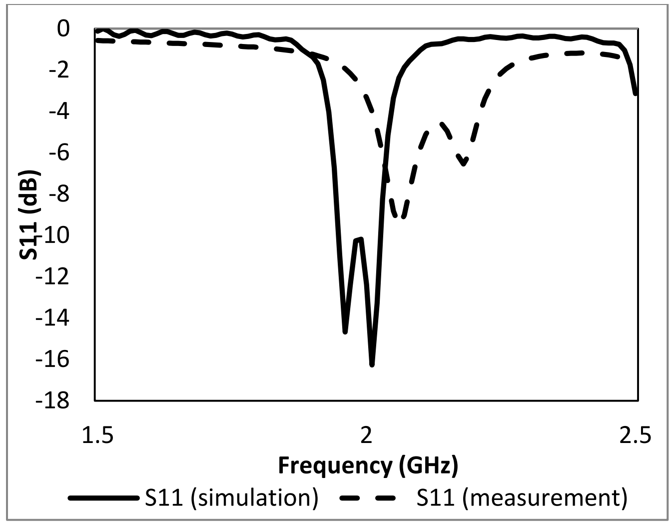


Figure 15. Simulated and measured results of integrated rectangular SIW filter and rectangular microstrip patch antenna designed at 2 GHz

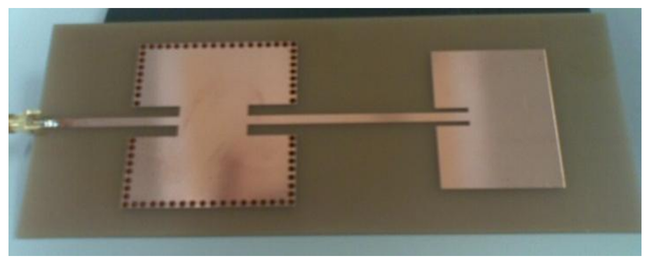


Figure 16. Photograph of physical cascaded structure between the rectangular SIW filter and rectangular microstrip patch antenna

The design is then applied on the simulation of a multilayer structure for a microwave filter and antenna, as shown in Fig. 17. Fig. 18 shows the radiation pattern for the multilayer structure at 2 GHz. The pattern represents a main lobe magnitude of 4.1 dB at a 180.0 degree direction from the origin point. The E-field pattern for the multilayer rectangular SIW filter and microstrip patch antenna at 2 GHz is shown in Fig. 19. The simulation results show that the magnitude of E-field is concentrated at the center of the SIW cavity, whereas the antenna cavity exhibits less concentration because it is a radiating device. A return loss of -24.65 dB and bandwidth of 62.98 MHz was achieved, particularly in the passband, as shown in Fig. 20.

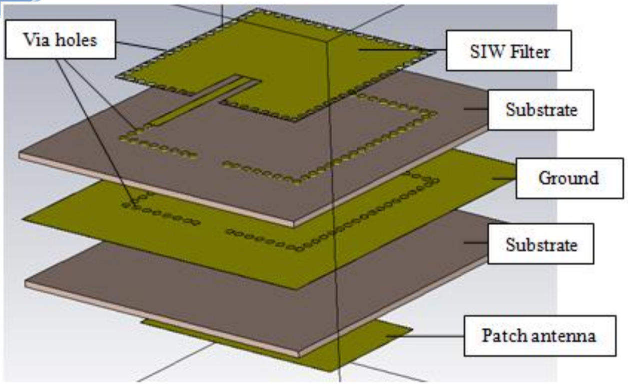


Figure 17. Multilayer structure between SIW filter and microstrip patch antenna

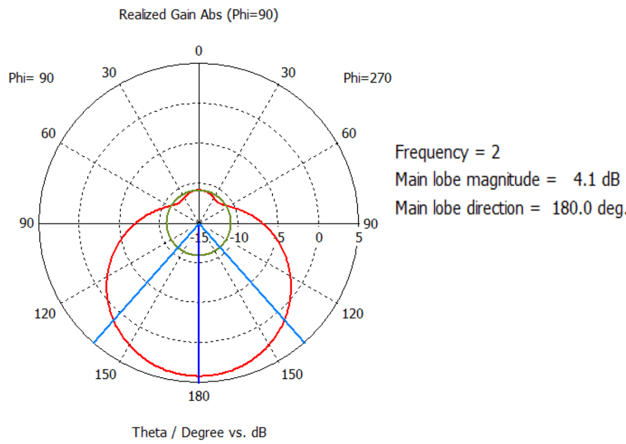


Figure 18. Simulated radiation pattern for multilayer at 2 GHz

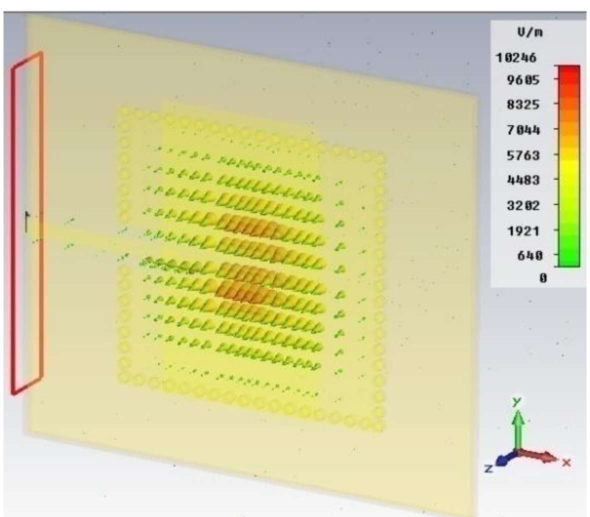


Figure 19. E-Field distribution of multilayerrectangular SIW filter and rectangular microstrip patch antenna integration in single mode (TE_{10}) at 2 GHz

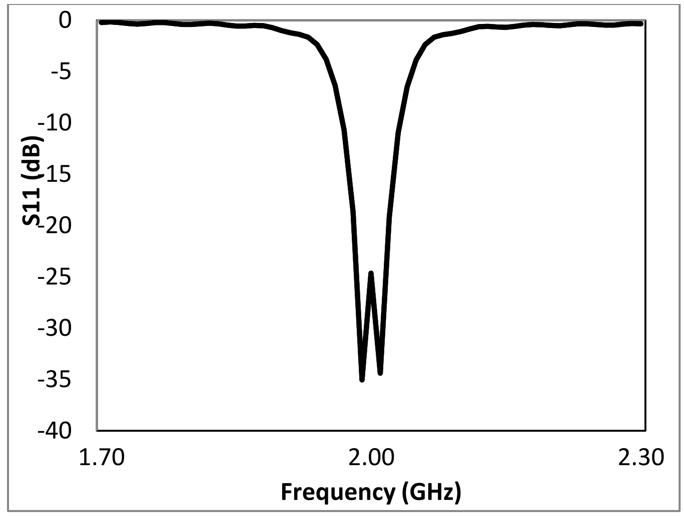
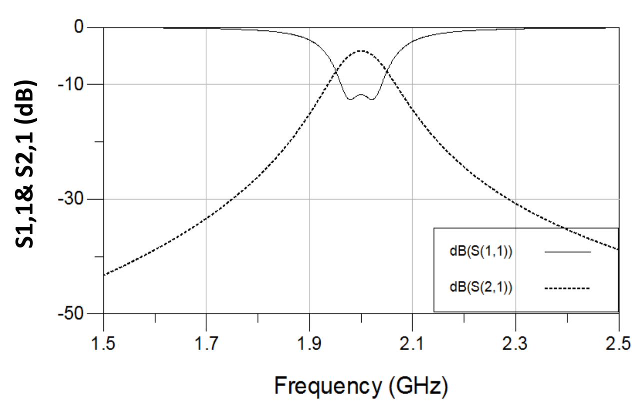


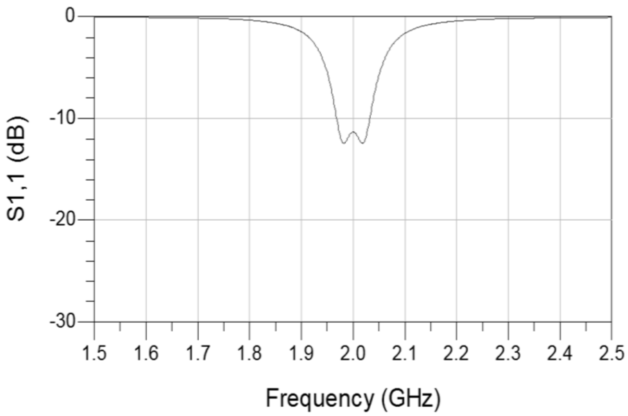
Figure 20. Simulated response of multilayer rectangular SIW filter and rectangular microstrip patch antenna integration designed at 2 GHz

B. Dual-mode

We further analyzed the dual-mode topology for a microwave filter and antenna through simulation. The values for couplings are $K_{01} = K_{23} = 50$ and $K_{12} = 59.85$ with capacitance $C_1' = C_2' = 42.56$ pF and inductance $L_1' = L_2' = 149.23$ pH based on Fig. 3(a). Fig. 21(a) shows the simulated results of the dual-mode filter based on a lumped element equivalent circuit. A return loss (S_{11}) better than -12 dB and insertion loss (S_{21}) of -4 dB with a bandwidth of approximately 100 MHz were achieved. For the dual-mode antenna, the coupling values for $K_{01} = K_{12} = 50$, capacitance $C_1' = C_2' = 52.92$ pF, and inductance $L_1' = L_2' = 119.69$ pH were obtained based on Fig. 5(a). Fig. 21(b) shows the simulated results of the dual-mode antenna based on a lumped element equivalent circuit. A return loss S_{11} better than -12 dB with a bandwidth of approximately 65 MHz was achieved.



(a)



(b)

Figure 21. Simulation results of lumped element equivalent circuit for dual-mode (a) filter and (b) antenna

The design of the dual-mode filter (TE_{20} mode of propagation) based on the SIW cavity with E-field is shown in Fig. 22. The analysis shows that the distribution of E-field with two circular propagations is observed in the single SIW cavity filter. Fig. 23 shows the simulation results of the dual-mode SIW cavity filter. A return loss (S_{11}) and insertion loss (S_{21}) of approximately -17 and -1 dB, respectively, with a bandwidth of approximately 195 MHz were obtained.

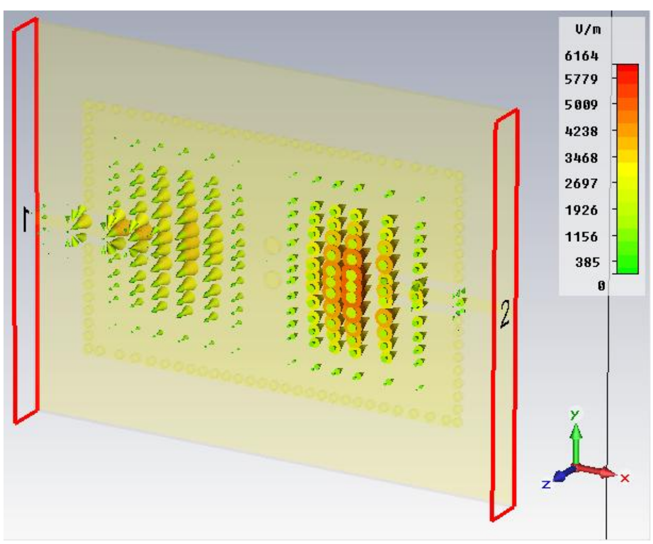


Figure 22. E-field distribution of rectangular SIW filter in dual-mode (TE_{20})

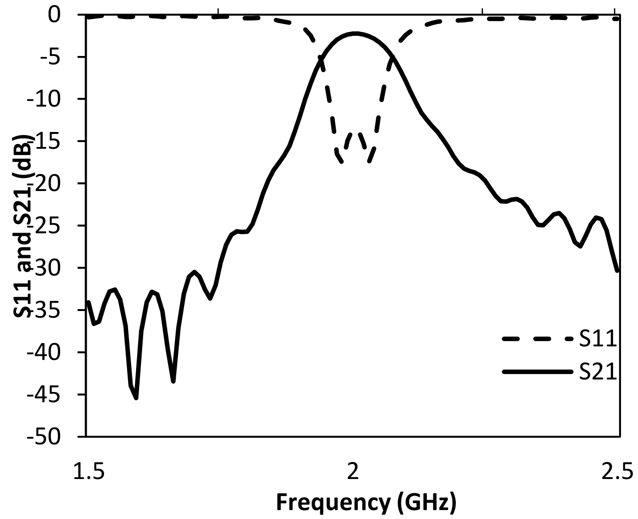


Figure 23. Simulation results for dual-mode rectangular SIW filter at 2GHz

For the dual-mode antenna, investigations of the E-field pattern behavior based on the rectangular microstrip patch are shown in Fig. 24. In this topology, a perturbation notch is introduced to separate two orthogonal modes in the microstrip patch antenna cavity. Fig. 25 shows the simulated results of the dual-mode antenna. A return loss (S_{11}) of approximately -14 dB with a bandwidth of 84.1 MHz was achieved in the passband.

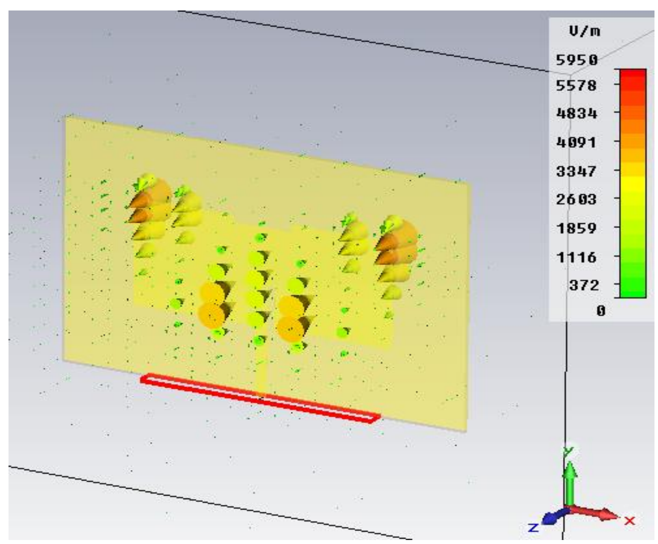


Figure 24. E-field distribution of rectangular microstrip patch antenna in dual-mode (TE_{20})

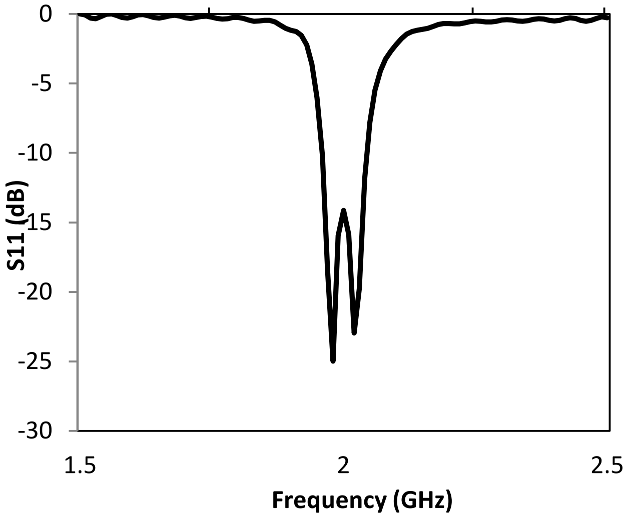


Figure 25. Simulation results for dual-mode rectangular microstrip patch antenna at 2 GHz

An analysis is then conducted on the proposed dual-mode cascaded integration between the microwave filter and antenna. The designed coupling values $K_{01} = K_{34} = 50$ and $K_{12} = K_{45} = 55.28$, capacitances $C_1' = C_2' = 42.43$ pF and $C_3' = C_4' = 38.58$ pF, and inductances $L_1' = L_2' = 149.22$ pH and $L_3' = L_4' = 135.65$ pH are based on Fig. 5(b). Fig. 26 shows the simulated results of equivalent circuit for cascaded integration. A return loss (S_{11}) better than -12 dB with bandwidth of approximately 95 MHz was achieved.

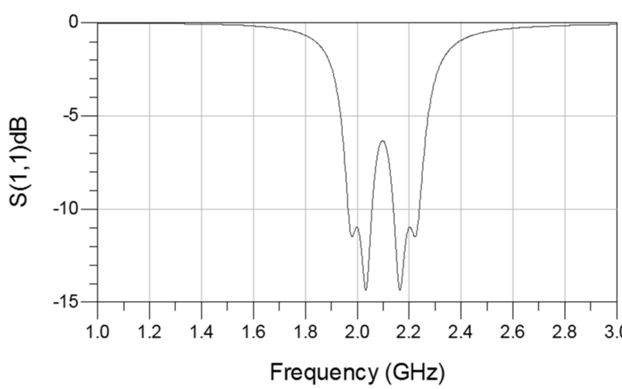


Figure 26. Simulated results of equivalent circuit for cascaded integration design

The E-field pattern for the dual-mode integrated rectangular SIW filter and rectangular microstrip patch antenna at 2 GHz is shown in Fig. 27. The S-parameter response of the integrated filter and antenna is shown in Fig. 28. A return loss (S_{11}) better than -30 dB with bandwidths of approximately 48.95 and 57.00 MHz was achieved.

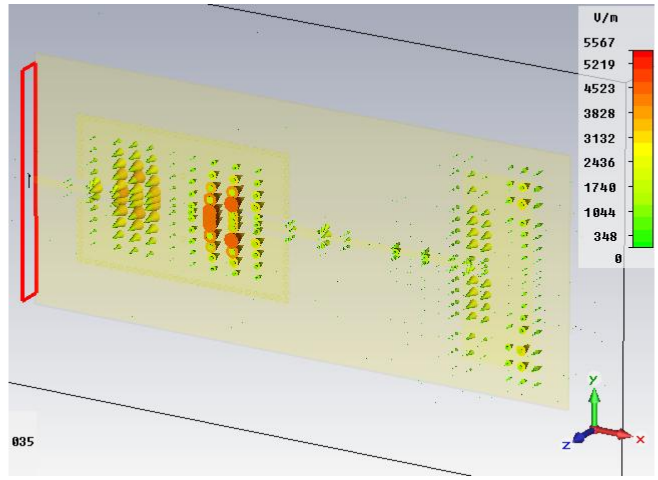


Figure 27. E-Field distribution of integrated rectangular SIW filter and rectangular microstrip patch antenna in dual mode (TE_{10}) at 2GHz

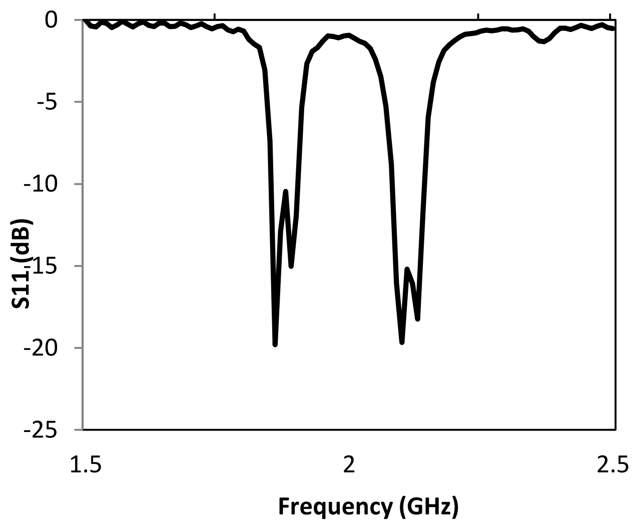


Figure 28. Simulation result of integrated rectangular SIW filter and rectangular microstrip patch antenna in dual mode

V. Conclusion

In this paper, the realization of an integrated rectangular SIW filter and rectangular microstrip patch antenna was successfully presented. A new technique to produce the single- and dual-mode of the rectangular SIW filter and rectangular microstrip patch antenna based on the resonant circuit approach was developed. The EM simulated results show good agreement with the ideal circuit. The experimental results of the cascaded integration show good agreement with and are in-line with the simulated performance. The multilayer integration between the rectangular SIW filter and rectangular microstrip patch antenna was simulated to reduce the overall physical volume significantly. Investigations on an integrated SIW filter and antenna will be conducted in future works to analyze and characterize the performance of such integration to produce a new class of integrated filter and antenna in a multilayer structure. This new class of

integrated filter and antenna that can produce a filtering and radiating element in a single device would be useful in microwave RF front systems where the reduction of overall physical volume and cost are important.

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